EFFECTS OF VISUAL AIDS WITH AXIS INFORMATION ON NAVIGATION AND USER EXPERIENCE IN VIRTUAL REALITY

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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May 2020

Major Subject: Computer Science

ABSTRACT

The widespread use of Virtual Reality(VR) has triggered many interesting practices in the field of visualization. This work presents one such visualization, Microvascular Network of a Mouse Brain in VR. Any VR application requires a certain amount of navigation irrespective of the visualization. This research has implemented multiple visual aids for navigation in non-human scale visualization of Microvascular Data. An experiment is presented to test how users experience and interpret these visual aids. The visual aids were designed to provide users with varying levels of information in terms of axis and location. Feedback from users indicates the effect of the visual aids on the navigation as well as their VR experience.

DEDICATION

To my father, my mother, and my husband, who have been my constant strength and support throughout the ups and downs of my life.

ACKNOWLEDGMENTS

I would like to thank my Advisor, Dr. John Keyser for guiding me with this thesis work. I would like to thank all of my friends and peers from Aggie Graphics Group for helping me directly or indirectly with this work. I would also like to thank Dr. Micheal Nowak for his help with KESM data. Finally, I would like to give special thanks to Texas A&M University for giving me the opportunity of conducting this research.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supported by a thesis committee consisting of Professor Dr. John Keyser and Dr. Theodora Chaspari of the Department of Computer Science and Engineering and Professor Dr. Ann McNamara of the Department of Visualization.

All other work conducted for the thesis was completed by the student independently.

Funding Sources

Graduate study was supported by graduate teaching and research assistant-ship from Department of Computer Science and Engineering, Texas A&M University.

NOMENCLATURE

VE	Virtual Environment
VR	Virtual Reality
KESM	Knife Edge Scanning Microscopy
VTK	Visualization Toolkit
SD	Standard Deviation

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1. INTRODUCTION

Three dimensional representation has been used for scientific visualization for a while now. This practice has led to the widespread use of desktop and immersive virtual environments(VE) for research and industrial purposes. Continuous development in this sector has made the use of Virtual Reality(VR) more accessible. Like many other fields, this has initiated many interesting practices in the field of visualization as well. These visualizations range from console games to training simulations, medical purposes and so on.

The representation of the virtual environment is still highly domain dependent [2]. Some domains may require desktop virtual environments while some domains require highly immersive environments with head mounted devices. Irrespective of the representation or domain, if the environment requires any type of movement inside it, the system has to provide some navigational aid for that. Thus navigation is considered to be an integral part of VR applications [3].

There are many common practices to provide navigational aids in virtual environments. Most of the desktop VE applications use keyboard or mouse input for navigation and interaction, whereas more immersive VE applications use hand controllers to move around inside and interact with the environment. Apart from navigational aids that are being used, the technique of navigation also differs with the VE being presented. Navigation techniques used in small scale or familiar environments will differ from large scale and non familiar environments [4]. For environments that are not human-scale models, it can be difficult to orient and move through the environment. Keeping this in mind, researchers have come up with many effective navigational techniques. Multiple research studies have been done to test and compare navigational techniques' effectiveness in different representations that range from familiar landscape environments to non-familiar large scale environments with occlusion.

There are many interesting visualizations that need to be investigated for proper navigation techniques. For example, for an environment that represents a large network or maze that looks exactly the same in every direction and is non-human scale, traditional navigational techniques might or might not work for that. The motivation of this work is to explore the visualization of one such type of data- a microvascular network of the mouse brain (Figure 1.1). Microvasculature is the network of capillaries that complete the loop between arteries and veins. In contrast to the tree-like topology of larger-scale vascular structures seen in traditional biomedical data, microvasculature tends to have a network structure [1]. Knife edge scanning microscopy has made it possible to get large volumes of microvascular data in very high resolution. The current visualizations that exist for this are volumetric rendering of the scanned data. One of the motivations of this research is to visualize the microvascular network in a massive scale in virtual reality and to explore different aspects of such a visualization.

The type of visualization mentioned above requires a virtual environment with special navigational techniques so that the users can be guided through the large network-like environment. This thesis implements and tests different existing navigational techniques in the proposed virtual environment. The aim is to test how users interpret these existing navigational techniques in such environments. Visualization of the microvasculature network is done in an immersive virtual environment with different visual aids for navigational purposes. These visual aids provide users with different levels of axis information. A user study is performed to collect user feedback for the implemented visual aids for navigation. To compare and contrast between different visual aids, several performance metrics are considered. The collected data is analysed later to suggest which visual aids are better for navigation in our proposed visualization.

The purpose of this research is summarized as-

"development and comparison of different visual aids with varying levels of axis information to navigate in large three-dimensional virtual environments"

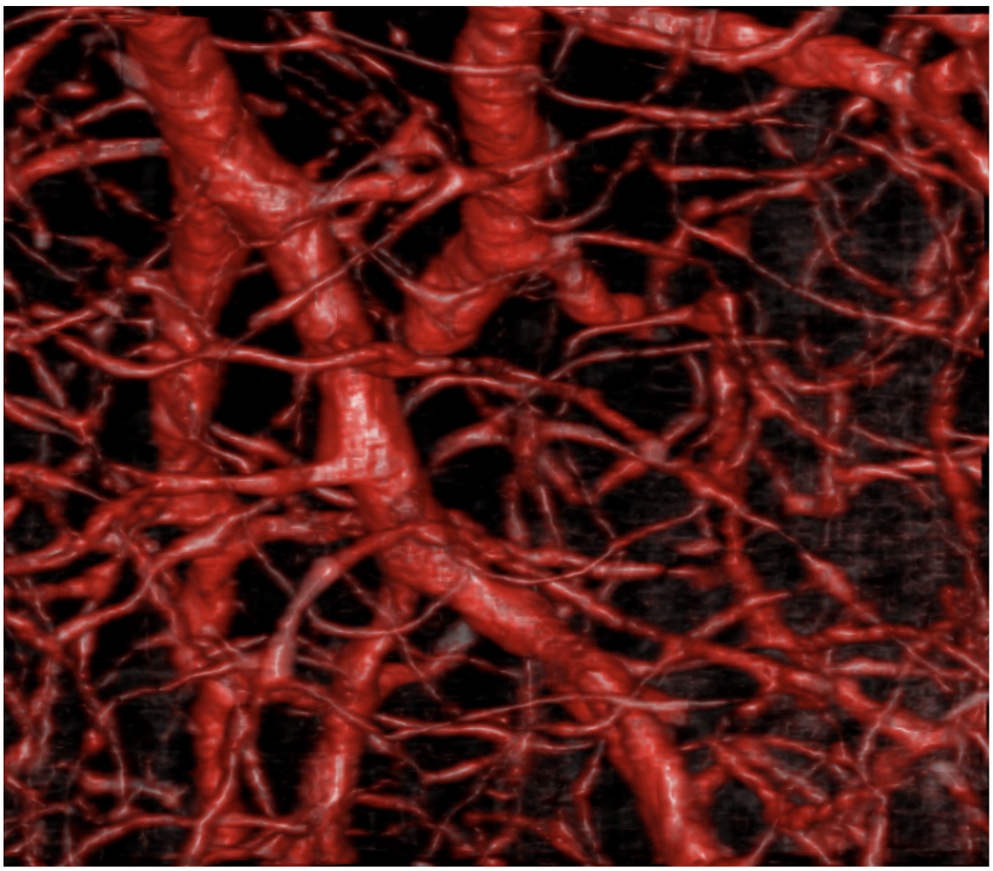


Figure 1.1: (Reprinted from [1]) Microvasculature Network of Mouse Brain

2. MOTIVATION

The conventional meaning of navigation refers to movement through a specific environment. VR experts believe navigation consists of two parts: *wayfinding* and *travel*. *Wayfinding* is the cognitive component of navigation where the user makes decisions about their current and future position in the environment. Multiple small decisions results in *travel* through the environment. *Travel* is related to the motion itself and does not require any decision making [4].

While providing users with navigational aids, it is important to maintain the features that define VR. It is essential to preserve these features in order to provide users with a full VR experience. Two such features are *Immersion* and *Presence*. *Presence* is defined as the sense of being in an environment. In other words, it is the sense of being in the environment presented via the virtual world [5], a psychological phenomenon related to the sense of the user [6]. *Immersion* is more objective. It is the amount that represents how much immersed a user is inside the VR world. From technical point of view, *Immersion* intends to convey the belief to the user that he has left the real world and is transported in the virtual environment, [7] i.e. how much real the virtual world seems to the users. That being said, to meet both of these features of virtual reality, a proper navigation technique is an integral part. A poorly designed navigation technique can require a user to move back and forth between the virtual-world and real-world multiple times to make sure they are navigating in the correct way. Doing so spoils “Presence” and “Immersion” both.

Various research has been done to investigate different navigational techniques in virtual environments. However, large scale virtual environments with occlusion and similarity in every dimension is still a field to be studied for navigation techniques. With development of VR, it is being used in more environments that are not human scale and outside human experience. These types of environments need investigation on how users interpret and use traditional navigational techniques in such environments. Hence in this thesis, a non-human scale and non-familiar virtual environment is being developed and experimented with, in order to evaluate different navigational techniques.

The navigational techniques tested differ based on the visual aids provided. These visual aids provide different amounts of information to the users. As explained above, wayfinding inside VEs is the cognitive component of navigation and thus requires knowledge about current, future and past location. Hence, the visual aids in this research provide axis information to give users a sense of their location. The experiment is carried out to test how these visual aids affect navigation and user experience.

3. GOALS

As stated earlier, the aim of this thesis is to visualize large, non-human scale, network-like data in a three dimensional immersive virtual environment and study user interpretation of different navigational techniques with respect to this environment. The main goal of this work can be divided into the following sub-goals:

3.1 Visualization

The first goal is to generate a large network for the virtual playground that has no specific landmark or point to distinguish between up-down, front-back and left-right. The goal is to make a 3D maze-like virtual environment to test different navigation aids with different levels of axis information.

3.2 Navigation

The second goal is to design and implement different navigational aids and visual cues to guide users inside the visualization proposed above. As the virtual environment will consist of a large 3D network with no visible sense of axis, the visual cues will provide information about the axis in a controlled way.

3.3 User Study

The third goal is to design a user study to test the different visual aids designed in step 2. The goal of the user study is to test which visual aid works best in terms of navigating inside the proposed network. The study data can help to understand exactly what amount of axis information should be provided in order to navigate quickly and easily. Along with this, the study will also give insight on the level of comfort while flying through such an enormous network.

3.4 Analyses

The fourth and final goal is to analyze the user feedback based on different performance metrics. The amount of time, ease in use, and success in completing the study will give insight on what visual aids are best suited for this environment. Also, analyses of users' backgrounds will reveal important information on how to design VR applications for people with different levels of expertise.

4. PREVIOUS WORKS

4.1 Microvascular Data Visualization

Existing works on visualization of microvascular networks consist of volumetric rendering for different purposes. Mayerich et al. [1] constructed a microvascular data visualization from knife edge scanning microscopic data via volumetric mapping and dynamic tubular grids. The goal was to understand the microvascular structure to investigate chronic diseases. In another work, [8], the authors implemented a hardware accelerated tracing algorithm to trace filament networks and construct the volume in faster way. They have also worked on efficient storage mechanisms for large amounts of data.

4.2 Wayfinding and Navigation

Work has been done previously on wayfinding and spatial orientation in VR. Most of these works are based on conventional landscapes. Darken et al. [9] presented navigation as a combination of wayfinding and motion. They have proposed some navigation tools i.e. Maps, Trails, Landmarks or directional elements like true north or sun. Apart from navigation they also discussed organizational or orientation remedies i.e. using landmarks or showing viewpoints to help orient in space. A problem is that their proposed wayfinding and orientation model may work only for city-like landscapes and may not be suitable for more complex spaces. In another work [10] the authors talked about mental maps. They discussed the necessity of mental or cognitive maps. The authors talked about different locomotion in virtual worlds and the form of locomotion that can be best to use. Bowman et al. [4] talked about the importance of way finding in spatial orientation and gave an example on how in a new place, drivers get less sense of spatial orientation as they are continuously involved in decision making. Later they presented an experiment to prove this theory. Galyean et al. [11] presented a novel navigational method called "The River Analogy". This analogy can generate a more narrative and immersive VR experience by continuously incorporating users' input with current space and time and guiding users on a path. Their work is now a part of the permanent collection at the Chicago Museum of Science and Industry.

4.3 Visual Aids

Many works have been done providing different visual aids for navigation. Darken et al. [9] presented different visual aids as navigational tools that can be mixed and matched for different VE applications. They have experimented with several navigational aids i.e. Maps, Markers, Landmarks, Trails etc. Their results show that users tend to perform better with maps and markers. Siegel et al. came up with another useful work on spatial knowledge, referred to as LRS (landmark route survey) in most existing works on spatial orientation [12]. Darken et al. [13] presented an electronic map for overview of the VE. In a later work [14] they studied the usefulness of such overview maps on users' navigation.

Some works are done to find out the drawbacks of these visual aids. Darken et al. [15] pointed out the fact that using a map can force a user to change perspective every now and then and hence can spoil the idea of presence and immersion. Chittaro et al. [16] [17] presented some more interesting visual aids like a 3D Web-map to guide users indirectly or even a humanoid guiding users directly, showing the path inside the virtual environment.

4.4 User Experience

Researchers have investigated and conducted lots of study to compare and contrast between different navigational tools. Burigat et al. [3] experimented with different location-pointing navigational aids i.e. 2D and 3D arrows. In this work they have compared three special types of visual aids i.e. 2D arrow, 3D arrow, and Radar in both familiar and non-familiar environment. Their results revealed interesting findings about these visual aids, including importance of prior experience of the user as well. Bowman et al. [18] did a spatial orientation awareness experiment where they tested on users' knowledge of their own position and objects' positions inside the VE. In a later work [19] they experimented with travel techniques more specifically steering techniques for traveling inside the environment. They compared a user's pointing, gazing, and torso direction while traveling.

Bowman et al. [4] conducted an experiment to compare between different travel techniques in an immersive virtual world. Their work considered occlusion within large-scale environments. Their goal was to find how travel technique affects a user's spatial orientation. Results showed that path dimension as well as users' sophistication significantly affects their performance.

5. METHODOLOGY

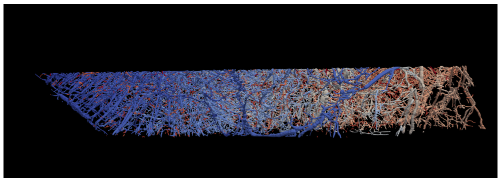
The workflow of this research is carried out in a sequence of subsequent stages. The first stage is to create a VR application that visualizes the Microvascular data in a non-human scale manner. The development of this VR application is followed by providing navigation or travel techniques inside the VE. The travel techniques are incorporated with the visualization to get the finalized version of the VR application. The third stage is to design and implement the visual aids. This is the stage where the cognitive part of the navigation is taken care of. The fourth stage is to design and conduct a user study to test user experience in the developed VR application. The final stage is to analyze the data collected from the user study to draw conclusions on best VR practices in VEs like this. All five stages are described in more detail in the following sections.

5.1 Visualization

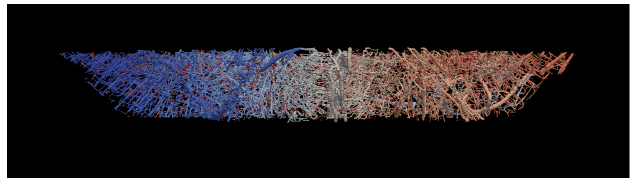
The main element of the VE application developed in this thesis is the visualization of the microvascular network of a mouse brain. The goal of this visualization is to create a VE that does not resemble a familiar scene to any user. Another criteria expected from this VE is that the main navigational area should look almost the same in every direction. This is because we want the user to not use any landmark and feel lost in terms of spatial orientation while navigating inside the VE.

5.1.1 ParaView

For visualization, knife edge scanning microscopy data for the microvasculature network of a mouse brain is used. The original format of these data are in the VTK (Visualization toolkit) format. An entire mouse brain was scanned into 10 slices. The VTK file for each of these slices ranges from 30MB to 500MB. For our visualization, we picked the first three slices of the mouse brain and concatenated them to visualize the lower half of the brain. Each of these slices are later clipped in ParaView to give them a rectangular shape. The visualization of a single slice in ParaView is shown in Figure 5.1 .



(a)



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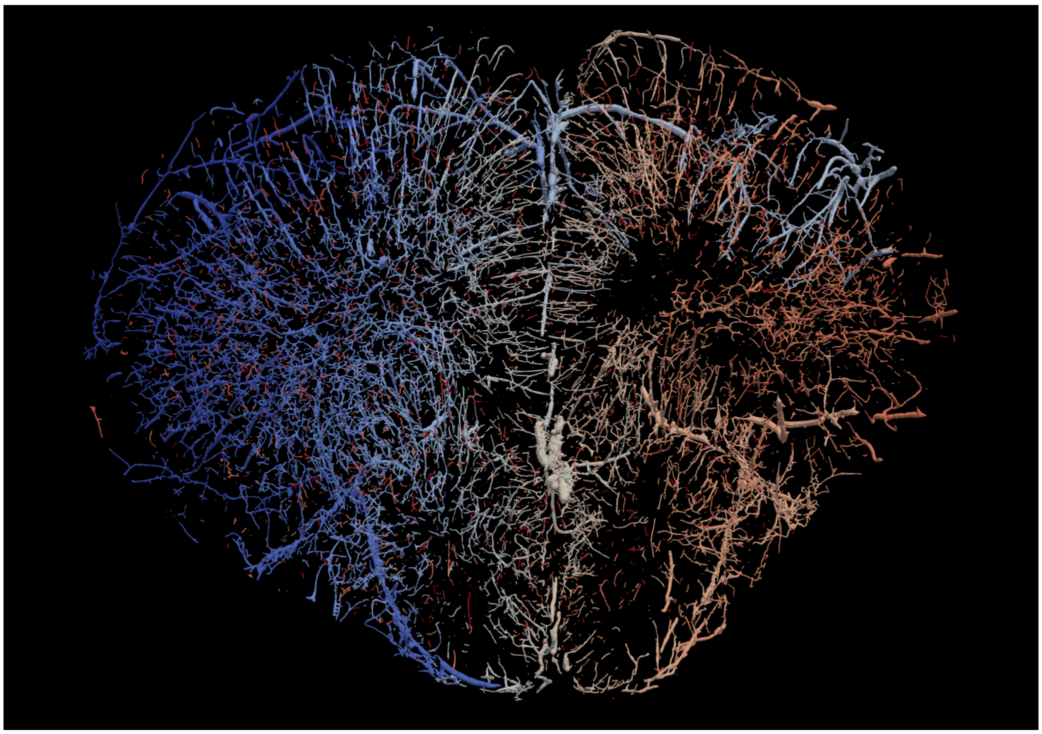


(c)

Figure 5.1: Visualization of a single slice of KESM data in ParaView from (a) front (b) left (c) top

5.1.2 Unity

The visualization application is implemented by using Unity. As VTK files are not directly compatible with Unity, before visualizing, the data format is converted to Wavefront .obj so that it is compatible with visualization in Unity. The clipping and conversion is done in ParaView. The rectangular shaped slices are stacked on top of each other in Unity to create a rectangular shaped block of microvascular network. The whole network is scaled up to a certain level so that it appears big enough in normal human perception. The scaled and concatenated clipped slices in Unity that forms the half brain are shown in Figure 5.2.

Followed by the concatenation and scaling in Unity, texture mapping was done for the brain data. For the texture, a simple blood vessel texture was selected so that the network resembles an actual microvascular network. Global lighting was used to make the VE bright enough for the navigation.

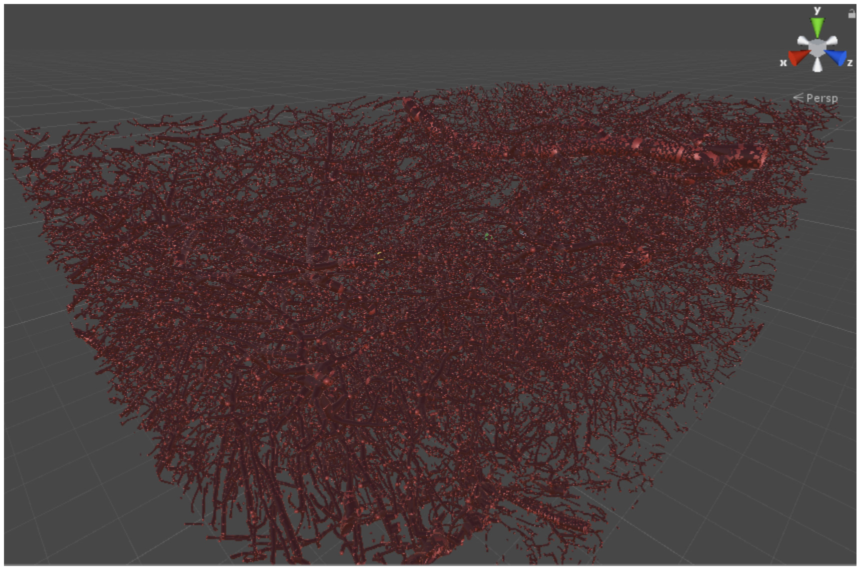
To give the network a rigid look from any position, default back-face culling was turned off in Unity. This step makes sure that the visualization does not change appearance while a user navigates inside the network. Without this step, the network will seem hollow from some locations and rigid from some other locations.

Another issue that occurs is the rendering of the farthest clipping plane. If that is too small, the distant view changes every time the user moves her head. To solve this problem, for this visualization, the farthest clipping plane is chosen to balance competing factors. We want it to be large enough so that the far view does not change all the time, and near enough that not too much information is included, so that rendering is still fast enough for interactive use. On top of this, a fogging mechanism is used so that even though there is a small change in rendering in the farthest plane, it's not recognizable. All these steps generate a smooth visualization of the microvascular network in Unity.

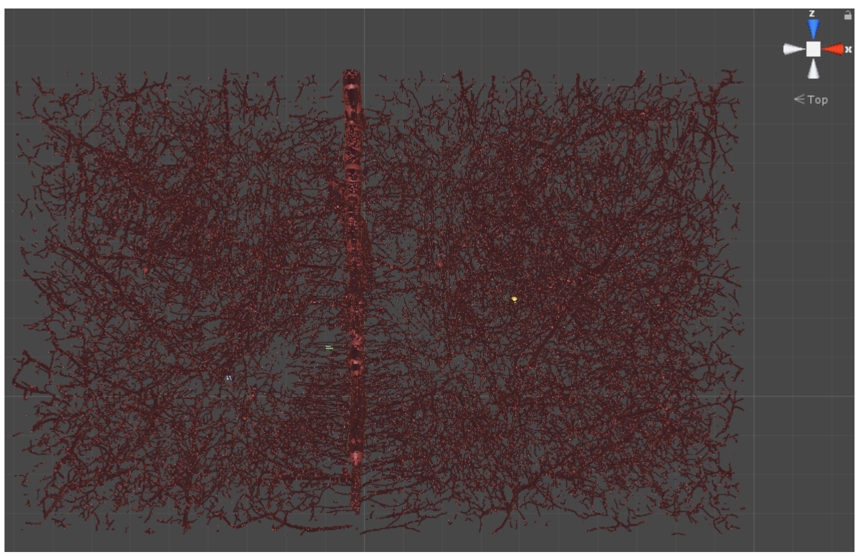
5.2 Navigational Technique

After the visualization is done, a navigational method is implemented in a manner so that users can fly through the microvasculature network in the VE. This is a seated VR application, so all the navigational method is implemented through the hand controllers. The user can remain seated and use the hand controllers to navigate and fly through the network.

For Navigation, the head mounted display device and hand controller of an Oculus Rift CV1 is used (Figure 5.3 , Figure 5.4). A C# script is added to the camera component of Unity to synchronize the movement of the Unity Camera and the default camera of the head mounted device. For the movement inside the VE, another C# script is added to the Unity camera component to make it behave as a first person controller. This script captures movement in the right hand controller and adjusts the position of the camera inside the VE accordingly.



(a)



(b)

Figure 5.2: Visualization of concatenated slices of KESM data in Unity from (a) back-left (b) top

Figure 5.3: Oculus Rift: Head Mounted Display Device

Figure 5.4: Oculus Rift: Hand Controllers with Implemented Navigation Modes

The initial position is defined inside the start() function of the unity camera component. The button of the right hand controller is captured continuously and based on the that, the position of the camera object is fixed every frame. The frame refresh rate for this application is 30 frames per second. The mapping of camera movement with the right hand controller's button is shown in Figure 5.4. The left hand controller is not used for navigation and is later used for visual aids instead. Another control that is implemented in this VE application is the pause and resume option. Unlike the other control, this was provided via the keyboard. Upon pressing the key "Esc" in the keyboard, the application will be saved in the background and paused. To resume the application, the same key is pressed.

5.3 Visual Aid

The completion of an entire visualization with navigational techniques is followed by implementing different visual aids. As mentioned earlier, the goal is to provide a user information about her location. Hence, the purpose of these visual aids is to provide users with axis information.

In this research, there are four different types of visual aids that provide different levels of information - no, one, two or three axis information.

5.3.1 None

In this version, all the user gets is the microvascular network itself to roam around. There is no visual cue or aids to help the user with navigation. The user performance in this version is later compared with other versions.

5.3.2 Skybox

The visual aid provides the knowledge of only up-down, giving only one axis of information. While navigating inside the VE, the user will be able to recognize only up and down in terms of location. This is done by adding a single Skybox as the global environment, where there is always a non-directional global lighting at the top of the network where users roam. The view of a user inside our VE with skybox is shown in Figure 5.5.

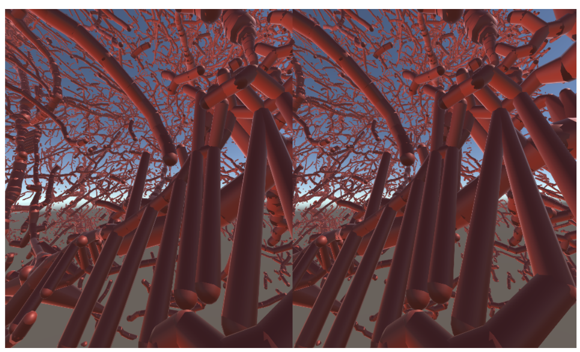


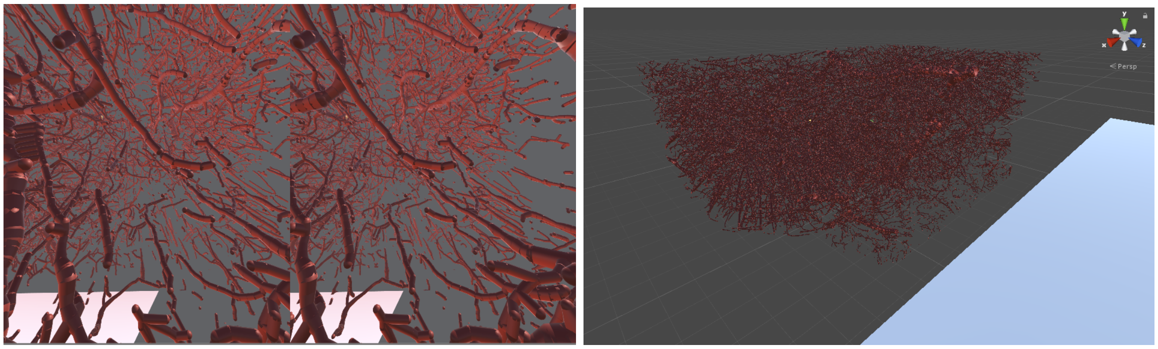
Figure 5.5: User view inside the VE with Skybox

5.3.3 Plane Sweep

This visual aid provides information in the form of a plane sweeping from one direction to another. This gives the XZ axis information. Unlike the skybox, it is not automatically provided to the users. Users have to press the X or Y button in the left hand controller to make the plane sweep through the network (Figure 5.6). This plane is aligned with the XZ axis and perpendicular to the Y axis. The plane sweeps in the direction of the Z axis. The plane provides information about the current position of a user inside the network in terms of depth. It also provides information about what orientation a user is at i.e. looking forward, right or left etc. Thus the plane provides information on location in Z axis and orientation in XZ plane.

This plane starts sweeping from the opposite side of the network with respect to the users' initial position (Figure 5.7 b). For this reason, the longer this plane takes to sweep across the current position of the user, the shallower the user is inside the network, and vice versa. Also, the direction from which the plane sweeps towards a user's current position indicates the direction of the user's view i.e. front, back, left or right. If it sweeps from left, that means the user is looking at the right side of the network. If it sweeps from front or right, that means the user is looking at the back or left side of the network respectively. The view of a user looking at the right side of the network while the plane is sweeping his position from the left is shown in Figure 5.7a. Thus, the sweeping plane provides information about the depth of users' positions inside the network and the direction they are looking at. Unlike the other visual aids, this visual aid is not readily present to the users and requires some decision making and calculation by the users.

Figure 5.6: Oculus Rift: Hand Controllers buttons for Visual Aids



(a) (b)

Figure 5.7: a) User's view inside the VE where the plane is sweeping his position from the left b) Initial position of the sweeping plane

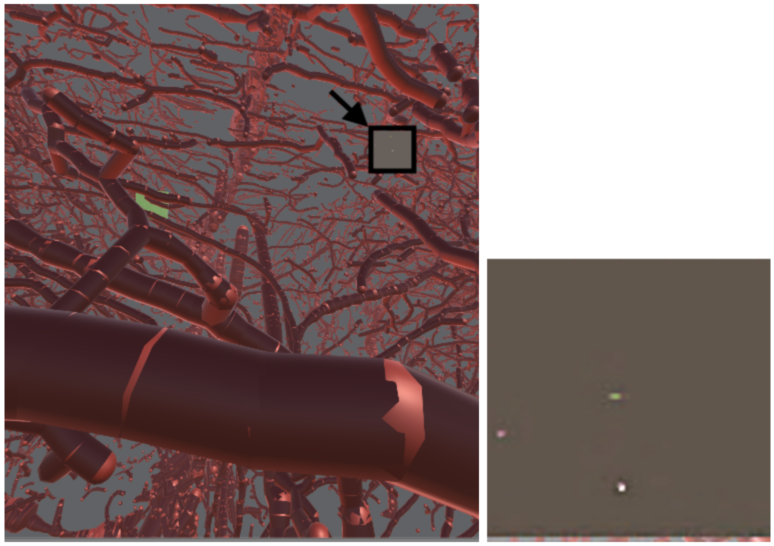
5.3.4 Minimap

The last visual providing the maximum amount of information, is the Minimap. This minimap provides a bird's eye view from the top of the network. The minimap is implemented by adding another camera component and making it capture the bird's eye view of the XZ plane from a positive Y direction. This camera component has a different z-index and is overlaid on the top of the main camera component described above. The minimap appears at the top right corner of the users' views. Hence, the user does not need to press any button to see the minimap and it presents information to the user in the most visible way possible.

The minimap captures the movement of the user (for this case the main camera component) in real time. The view of a user with the overlaid minimap and the minimap itself is shown in Figure 5.8. The white point in the map (Figure 5.8b) represents the user himself. The larger this point gets, the higher the user is inside the network. The other points are the hidden objects inside the network. Observing the proximity of the white point to other points, a user can understand his current position inside the network.

5.4 User Study

To test the efficiency of different visual aids described in the section above, a user study is designed and conducted. Before conducting the study, it has been approved by the IRB. The IRB



(a) (b)

Figure 5.8: a) Users' view inside the VE with an overlaid Minimap b) Contents of the Minimap

number for this study is IRB2019-1731D. The study design and execution process are as follows.

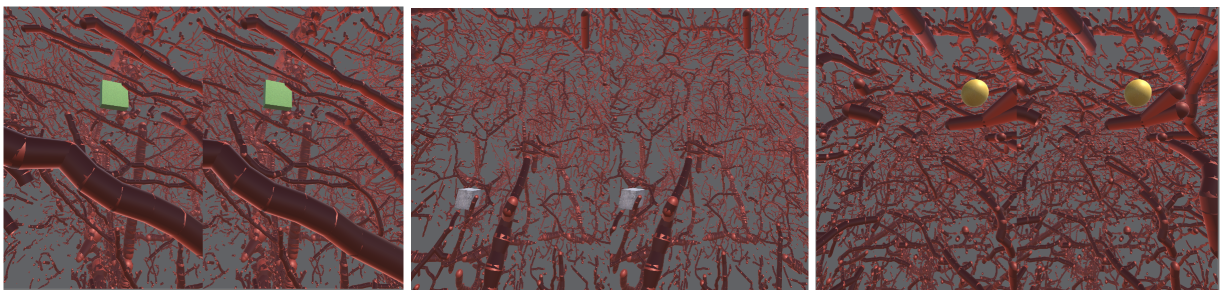
5.4.1 Study Design

This study is a between user study where each user experiences only one of the four visual aids for navigation. In each version of the study, the user has to complete a given task. During and after completion, users' feedback is collected for further analyses.

5.4.1.1 Task

The main task in all four versions is to find three hidden objects. These objects are hidden at three different locations inside the network. The location is chosen randomly and is the same across all four versions. The three hidden elements are further away from each other so that a user can not find that instantly by standing at the same position. The color of these objects are very distinct and different from the texture of the microvascular network in the VE. The three hidden objects that are included inside the network are: a green box, a grey box and a yellow sphere. A user has to navigate inside the network and find all three of the hidden objects. The views of a user inside the VE looking at these hidden objects are shown in Figure 5.9.

Before the study starts, a user is told the colors of all three hidden objects. They are told that if they reach to a reasonable distance from the objects, where they can identify it to be of a certain color, they need to click the controller button in order to register the timestamp of finding each object.



(a) (b) (c)

Figure 5.9: View of a user inside the VE looking at three hidden objects a) Green b)Grey c) Yellow

5.4.1.2 Performance metrics

As mentioned above, the feedback of the users is collected during and on completion of the study. The feedback is collected with respect to the performance metrics. The performance metrics selected for this thesis capture both quantitative and qualitative aspects of user experience while navigating inside the network. The four performance metrics used in this study are as follows:

- Time to Find All Three Hidden Elements
- Ease in Navigation
- Ease in Interaction
- Level of Discomfort

The first performance metric is selected to get feedback on how fast or slow a user can find all three objects. This is the quantitative data that is collected while the user is navigating inside the network. The rest of the performance metrics are qualitative in nature and are collected from post-study user feedback. These performance metrics are selected because in VR applications, the ease in interaction, navigation and comfort plays a significant role in *Presence* and *Immersion*. For the purpose of statistical analysis, in the feedback form, the later three performance metrics are encoded in 5 distinct values (A likert scale ranging from worst to best user experience).

5.4.2 Study Conduct

Fig 5.10 shows the steps in the study conduct procedure and what data is collected in which steps of the procedure. Upon signing a consent form and starting the study, a user has to fill out a form with some basic background information. In the background form, we encoded the level of users' VR expertise in 7 distinct values (a likert scale ranging from 1 to 7), where 1 indicates novice and 7 indicates highly experienced.

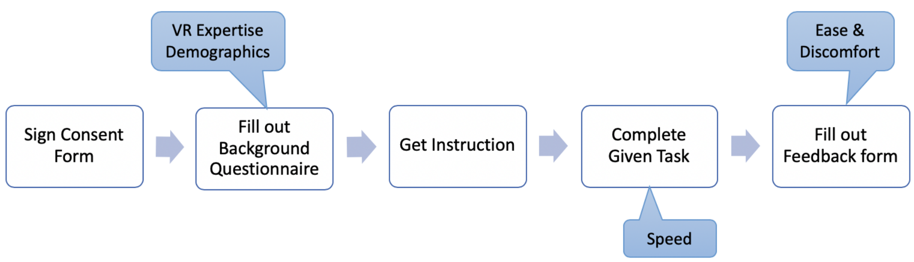


Figure 5.10: Steps in the study conduct procedure

After that, the users are given a general demonstration of how to use the VR hand controllers and head set and what is the task that they have to do. Then the users are helped with putting the headset on and grabbing the hand controllers.

When a user is ready, the study personnel starts the study and the user starts roaming inside the network with the help of hand controllers. They remain seated the whole time and can move their head around to look around inside the network. For the given task, whenever they find an object and can recognize it as one of the hidden objects, they will press the button (shown in Figure 5.6) in the right controller, and the timestamp for that operation is collected in a JSON file. Once a user finds all three objects, the study is considered to be done. Figure 5.11 shows the VR system setup for the user study.

After the study is done, the users fill out a feedback form stating their ease in navigation and interaction with the application and their level of discomfort while navigating inside the network.

Figure 5.11: A user navigating inside the microvascular network

5.5 Analyze Data

The data collected from the user study is analyzed to compare and contrast between different visual aids. A qualitative analysis is done to figure out the the effects of the visual aids on our selected performance metrics. The analysis gives some helpful insights about what type of navigational aid should be provided with this specific type of visualization and how to present information in the most useful way possible.

6. RESULTS

A total of 17 people participated in the user study conducted for this thesis. 11 of the participants were male and 6 participants were female. The age of the participants ranged from 18 to 54. 16 participants have the occupation of student. One participant is working in academia. 13 participants are from science and engineering background, 1 from public health, 1 from Geography, 1 from Liberal Arts, and 1 from Agricultural Economics. 16 participants finished the study successfully by finding all three objects. The data of one participant is excluded from the result analysis because of inability to follow the study instructions. Overall study time including filling out questionnaire forms and other procedures took no more than 45 minutes for any of the participants.

6.1 Analysis

As mentioned in section 5.4.1.2, data is collected to measure the effect of visual aids on the performance metrics. For finding out how the visual aids affect these performance metrics, a one way ANOVA is conducted on the collected data for statistical analysis. The independent variable in the ANOVA test is the visual aids. In each of the visual aid groups, there is data from 4 participants. The test is repeated 4 times to analyze the effect of all four performance metrics. The following graphs and charts show the mean and standard deviation for the performance metrics.

We have came up with 5 *Simple Hypotheses* to analyze the relationship of the performance metrics with visual aids and users' VR expertise. The following sections describes each of the hypotheses.

6.1.1 Hypothesis 1: Visual aid improves user performance

Table 6.1 shows the mean and standard deviations of the time for completing the given task for all four forms of visual aids. The results indicate that participants perform better with the plane sweeping. But due to the small number of people (4) in each group, the p-value provided by the ANOVA was very large (p-value > 0.707). This is the reason we can not say that there was any statistical significance. We conducted a TUKEY pairwise comparison on our data to compare each pair of visual aids with each other. The result of the TUKEY pairwise comparison is given in Table 6.2.

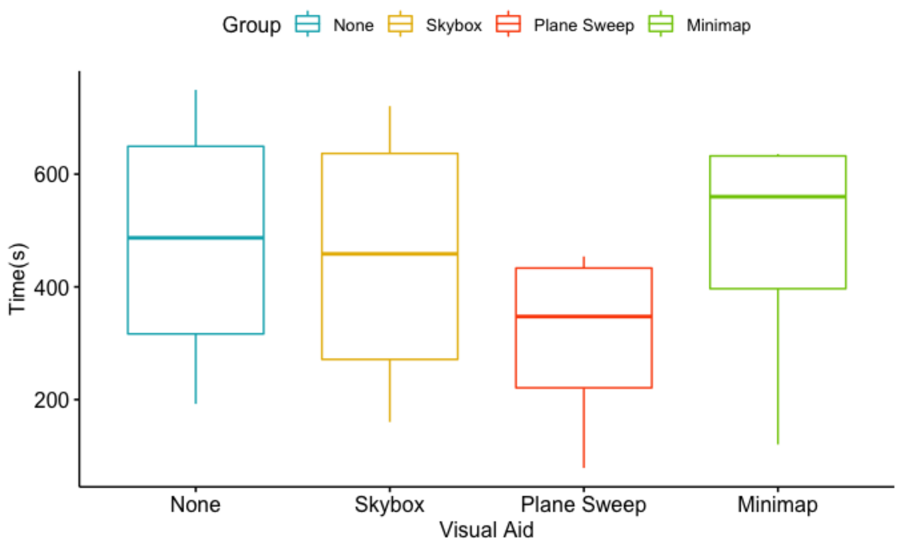


Figure 6.1: Visual Aid vs Time

Visual Aid	Mean	Standard Deviation
None	479	251
Skybox	450	260
Plane Sweep	307	173
Minimap	469	242

Table 6.1: Mean and SD of Speed

Figure 6.1 indicates the effect of the four different forms of visual aids on the speed of finding all three hidden objects. The Y axis shows time in number of seconds that users took to find three objects since starting navigating inside the network. The TUKEY test in Table 6.2 and Figure 6.1 indicates that having visual aids are better than not having any aids at all, however the p-values

Pairs of Visual Aids	diff.	p-value
Skybox-None	-29.444687	0.9978816
Plane Sweep-None	-172.107187	0.7298872
Minimap-None	-9.938894	0.9999175
Plane Sweep-Skybox	-142.662500	0.8237185
Minimap-Skybox	19.505793	0.9993790
Minimap-Plane Sweep	162.168293	0.7629331

Table 6.2: Tukey Pairwise Comparison of Visual Aids for Speed

are not sufficient to state this with certainty. Plane sweeping indicates better performance than the other three types. Skybox indicates better performance than providing no information. The results gave some indication of what might be the possible relative effectiveness but due to large p-values, we can not prove this hypothesis.

6.1.2 Hypothesis 2: Visual aid does not affect ease in interaction

Like the Hypothesis 1, we conducted the same ANOVA and TUKEY pairwise comparison test to compare between visual aids in terms of ease in interaction with the virtual environment. Table 6.3 and Table 6.4 shows the results of the statistical analysis.

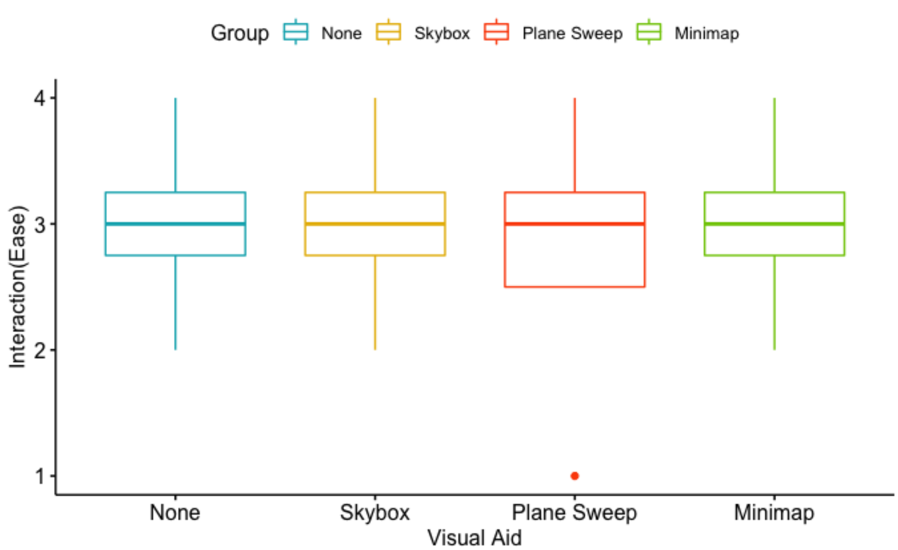


Figure 6.2: Visual aid vs Ease in Interaction

The results of the analysis and Figure 6.2 indicate that interaction with the VE does not depend on the visual aids that are used. The difference between the values are either very small or have no difference at all. The p-values are also very large in this case. Hence there is no statistical significance to claim that there is a difference in ease of interaction due to visual aids. Thus the Hypothesis 2 holds as it claims visual aid does not affect the ease in interaction.

Visual Aid	Mean	Standard Deviation
None	3	0.816
Skybox	3	0.816
Plane Sweep	2.75	1.26
Minimap	3	0.816

Table 6.3: Mean and SD of Ease in Interaction with the VR

Pairs of Visual Aids	diff.	p-value
Skybox-None	0.00	1.0000000
Plane Sweep-None	-0.25	0.9813794
Minimap-None	0.00	1.0000000
Plane Sweep-Skybox	-0.25	0.9813794
Minimap-Skybox	0.00	1.0000000
Minimap-Plane Sweep	0.25	0.9813794

Table 6.4: Tukey Pairwise Comparison of Visual Aids for Ease in Interaction

6.1.3 Hypothesis 3: Visual aid negatively affects ease in navigation

Table 6.5 shows the mean and standard deviation values of user feedback on ease in navigation. Table 6.6 shows the results of TUKEY pairwise comparison between each pair of visual aids. The results from the statistical analysis and Figure 6.3 indicates that presence of visual aids makes the navigation little to no easier. It also indicates the more information that is presented to the user, the less easy it is for them to navigate. We assume this might be due to the fact that, if more information is provided, it takes more time to process the information in order to complete the wayfinding component of navigation.

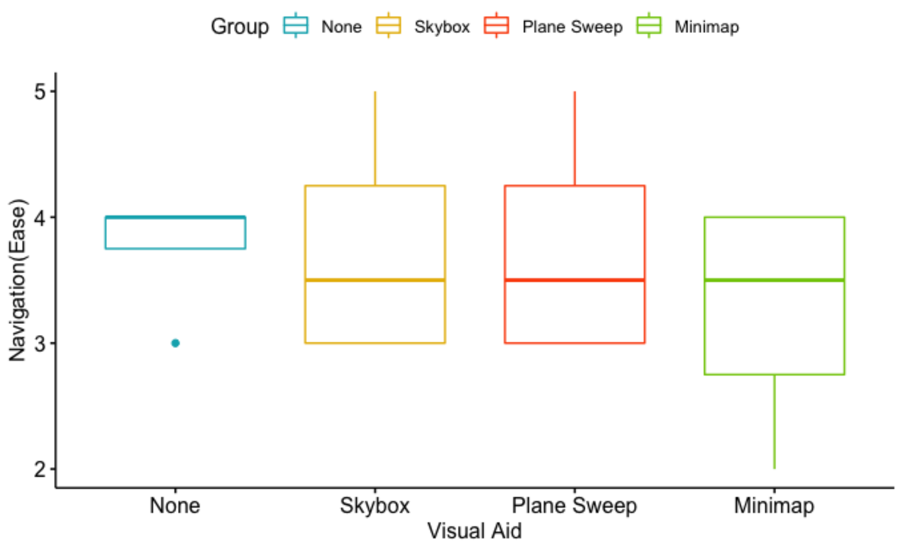


Figure 6.3: Visual Aid vs Ease in Navigation

The p-values we got in this statistical analysis are also very large, this is the reason we can not claim any statistical significance for the differences between different visual aids. As Hypothesis 3 claims that visual aids affect ease in interaction, with no statistical significance, this hypothesis is rejected.

Visual Aid	Mean	Standard Deviation
None	3.75	0.5
Skybox	3.75	0.957
Plane Sweep	3.75	0.957
Minimap	3.25	0.957

Table 6.5: Mean and SD of Ease in Navigation with the VR

Pairs of Visual Aids	diff.	p-value
Skybox-None	0.0	1.0000000
Plane Sweep-None	0.0	1.0000000
Minimap-None	-0.5	0.8455825
Plane Sweep-Skybox	0.0	1.0000000
Minimap-Skybox	-0.5	0.8455825
Minimap-Plane Sweep	-0.5	0.8455825

Table 6.6: Tukey Pairwise Comparison of Visual Aids for Ease in Navigation

6.1.4 Hypothesis 4: Visual aid increases level of discomfort

The analysis of user feedback on level of discomfort reveals an interesting aspect of the application. The results of the statistical analysis done in TUKEY pairwise comparison (in Table 6.8) show that with more information, the user discomfort increases. Even with just 4 users in each group, this claim is proved by lower p values (p-value 0.0017). The results show that with more information provided via visual aids, a user starts feeling more uncomfortable. Figure 6.4 also indicates with no additional visual aids, a user does not feel that much discomfort. On the other hand, if we present more information, the amount of discomfort gets a little bit higher. The fact to notice here is that the input range of discomfort ranged from 1 to 5, but all users' input was given in the range of 1 to 2. This indicates that the level of discomfort was not that high itself. But between visual aids, less information provided more comfort. We got statistical significance only for some of the pairs. So we can not strongly prove this hypothesis 4.

Visual Aid	Mean	Standard Deviation
None	1	0
Skybox	1	0
Plane Sweep	2	0
Minimap	1.5	0.577

Table 6.7: Mean and SD of Discomfort VR

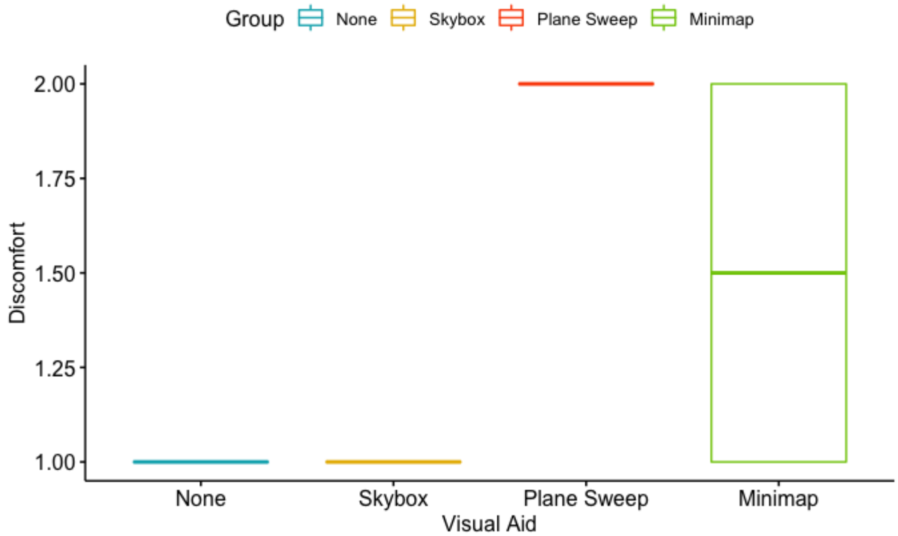


Figure 6.4: Visual Aid vs User Discomfort

Pairs of Visual Aids	diff.	p-value
Skybox-None	0.0	1.0000000
Plane Sweep-None	1.0	0.0017946
Minimap-None	0.5	0.1199630
Plane Sweep-Skybox	1.0	0.0017946
Minimap-Skybox	0.5	0.1199630
Minimap-Plane Sweep	-0.5	0.1199630

Table 6.8: Tukey Pairwise Comparison of Visual Aids for Discomfort

6.1.5 Hypothesis 5: VR expertise improves user performance

Apart from the visual aids, we also tried to run an analysis to see how the previous experience of users with VR affects the result. We conducted a "Pearson Correlation Test" to analyze the relationship between VR expertise and user performance. The mean, standard deviation and result of a Pearson correlation test is shown in Table 6.9 , Figure 6.5 and Figure 6.6 respectively.

The results of the Pearson correlation test indicates that the VR expertise and user performance are correlated with a correlation co-efficient of -0.34. This indicates that the more experienced the users are with VR, the less time it might take to finish the given task. The p-value of the Pearson

Correlation test is 0.2 , which again is not low enough to claim this hypothesis with statistical significance.

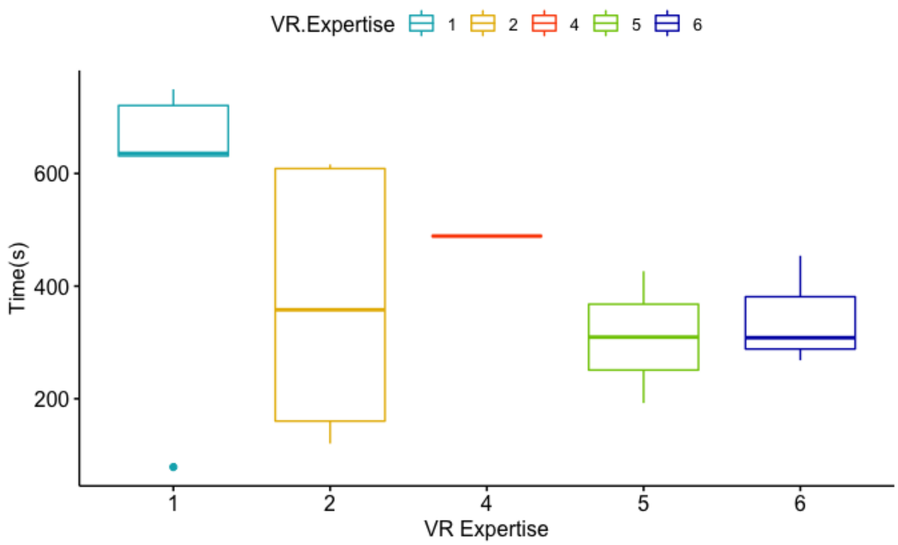


Figure 6.5: VR expertise vs Time

VR Expertise	Mean	Standard Deviation
1	563	276
2	373	237
4	489	NA
5	309	165
6	344	97.7

Table 6.9: Mean and SD of Speed

6.2 Observation

During the study, the study personnel observed the method of approaching the task by users. For users who are given the Skybox as visual aid, it appeared that users will go all the way to the top or a relatively top position to fly through and have a bird's eye view of the network. The users

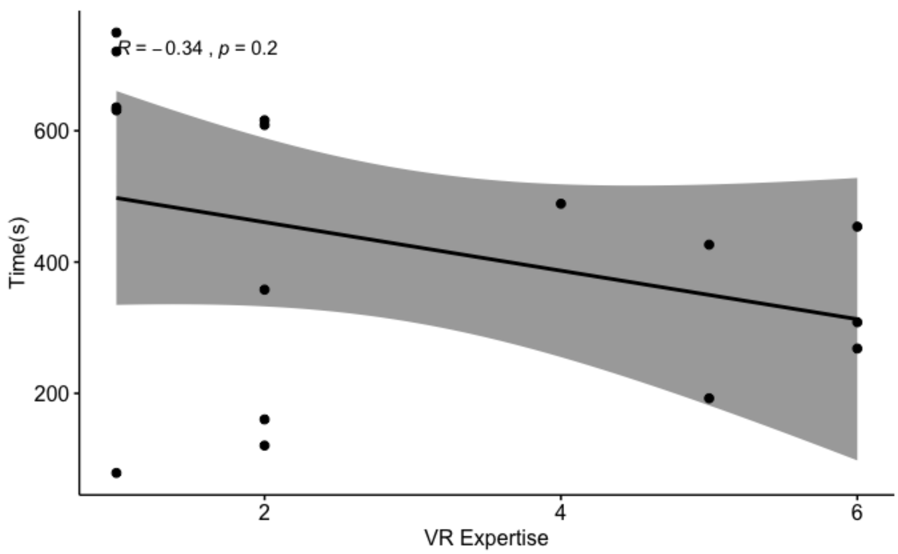


Figure 6.6: Pearson Correlation Test Between VR Expertise and User Performance

with plane sweep tend to not sweep it instead reaching the sweeping plane they start moving in another direction. Some of the users comments are as follows:

> "I felt lost after a while, but I used previously located element to navigate and find path"

> "It takes practice to get used to with amount of information provided . Once you grasp the information out there it is easier to navigate. After a while I could say I am this much height or so"

The study observation indicates that the user experience in VR affects a user's own interpretation and sophistication towards problem solving in such a large VE.

6.3 Discussion

The analysis of the user feedback and observation led to some interesting findings. The result suggests that, apart from the provided visual aids, the user behaviour depends a lot on their previous experience with VR. This led us to believe that the more a user spends time inside the VR, the better their performance will become.

As for the visual aids, the results indicate that with more information, the speed of finding the hidden elements is higher. But, at the same time, with more information, the ease in navigation decreases and discomfort increases among users. This led us to believe that although more information is better, it is also important to present them to users in a comfortable way to ease navigation.

Due to this fact, we concluded that to test the effect of visual aids, we should also take into account users' VR experience. Hence, the study to conduct this should be a within user study where each user experiences all four versions of visual aids. Also, in that case, the ANOVA test should be a two way ANOVA test where two independent variables should be "Visual Aid" and "VR Expertise".

Also, the statistical analysis gives very high p-values.The p-value is greater than 0.90 for visual aids and 0.20 for users' VR experience. This is due to the fact that there are only 4 participants' data in each of the group. This number is indeed very small and was not sufficient to tell if there is any statistical significance in the acquired data. For this reason, we concluded that for a subsequent study, more participants should be recruited for each of the subgroups.

7. FUTURE STUDY

The results of this research do not achieve any statistical significance due to the small number of participants in each group. Also, the results show the importance of users' VR expertise. For this reason, a further study can be designed with the feedback from this study. The results from this research suggest the following measures that should be followed for the subsequent study.

- The subsequent study should be an within user study where each user with a specific VR expertise will perform a given task with all four versions of visual aids. Hence, In the new study, there will be 8 to 16 subgroups instead of just four, depending on how many groups we divide VR expertise into. We intend to recruit more people in the subsequent study to get statistical significance and draw solid conclusions on the study results. We suggest to recruit atleast 10 people in each subgroup in order to observe any statistical significance.

- For making users more comfortable and familiar with the overall VR system and our application, the subsequent study should create and include a small practice test before starting the actual task. This should help users to familiarize themselves with VR, especially those users who have never experienced any VR application before.

- As mentioned above, the subsequent study should be a within user study, each user should experience all four versions of visual aids. To eliminate the effect of tiredness, the order in which they experience the visual aids should differ from one participant to another. Hence, this order should be generated randomly.

- For randomness, the position of hidden objects should be different in each version. If the hidden objects are in the same location, after the first time the users might find it easy to locate them. Hence the position of the hidden objects should be picked randomly and should be changed for each version of visual aids.

8. CONCLUSIONS AND FURTHER STUDY

This thesis has presented a novel visualization in VR. The visualization process addressed the issues in visualizing large scale, unfamiliar, network-like environments. The successful visualization combined with navigational techniques developed a novel VR application in this research.

A detailed user study has been conducted to address the issues encountered while navigating inside a network-like environment like this. The user study considered four performance metrics against some visual aids that are implemented as navigational aids. These performance metrics were compared and contrasted for all four versions of the visual aids to determine which method works best for navigation inside our VR application.

Although there was no statistical significance, the results indicated that with more information, the navigation task might get faster. At the same time the discomfort and difficulty in navigation gets higher as the users are required to process more information if the visual aid offers more information to them.

The study results also gave some indication that the user experience is not only affected by the amount of information provided to them but also how much previous experience they have with VR. This tells us that experienced users tend to be more comfortable with navigation and processing information in large networks. This points out the fact that with practice, VR experience gets better with time.

Due to not having statistical significance from the results of this research, a subsequent study design procedure is proposed. The subsequent study should be designed based on the findings from this research.

Thus, this research has highlighted some very important facts on how user studies for interaction and navigation in large scale network-like environments should be designed and conducted.

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